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13. ABSTRACT *(Maximum 200 words)*

We have successfully produced an optically triggered thyristor based in GaAs, developed a model for breakdown, and are developing 2 related devices, including a GaAs based static inductor thyristor. We are getting at the basic limitations of GaAs for these applications, and are developing models for the physical processes that will determine device limitations. The previously supported gas phase work – resulting in the back-lighted thyratron (BLT) – has actually resulted in a very changed view of how switching can be accomplished, and this is impacting the design of important machines. The BLT is being studied internationally: in Japan for laser fusion and laser isotope separation. ITT has built a BLT that has switched 30 kA at 60 kV in testing at NSWC Dahlgren and the device is being commercialized by another American company. Versions of the switch are now being tested for excimer laser and other applications. Basically, the switch, which arose from pulse power physics studies at USC, can switch more current faster (higher di/dt), with less housekeeping, and with other advantageous properties. There are a large number of other new applications, include kinetic energy weapons, pulsed microwave sources and R.F. accelerators.

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Optically triggered thyristor, GaAs, GaAs based static inductor thyristor, Back-lighted thyratron, Solid state switches

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FINAL TECHNICAL REPORT

The solid state work has made tremendous progress. Within ≈ 2 years, we have successfully produced an optically triggered thyristor based in GaAs, developed a model for breakdown, investigated and are developing 2 related devices, are getting at the basic limitations of GaAs for these applications, and are developing models for the physical processes that will determine device limitations. We have developed important collaborations, with Harold Fetterman of UCLA, Ch. Myles of Texas Tech, and Dan Dapkus of USC. The program has achieved these results based on collaborations that did not use excessive funding.

The previously supported gas phase work – resulting in the back-lighted thyratron – has actually resulted in a very changed view of how switching can be accomplished, and this is impacting the design of important machines. For example, Livermore is now considering a BLT-based redesign of an accelerator modulator output switch, in order to eliminate magnetic pulse compression, which has produced serious problems for ATA and ETA II at high repetition rates.

There are other important results. These include a hollow cathode electron beam, new means of microwave and millimeter wave generation, and important applications for high energy physics, including plasma based (wakefield-type) accelerators, and plasma lenses. The BLT is also a candidate for a plasma lens application at SLAC for studies of fundamental physics.

These results have demonstrated very significant progress in understanding the physics that limit development of solid state switches for pulsed power applications. (Attached is a paper on "Lock-on".) In addition, the work demonstrated optically triggered thyristor switching, and thus has made real progress towards implementation of the physics and development of pulsed power switches. Such switches will have applications for light weight, high power airborne and other applications - such as laser and accelerator pulsed power modulator components.

LIST OF PUBLICATIONS:

Refereed Publications:

1. "Phonon assisted indirect recombination of bound excitons in N-doped GaP, including near resonant processes," H. Dai, M.A. Gundersen, C. W. Myles and P. G. Snyder, Phys. Rev. B **37**, 1205 (1988).

2. "High power pseudospark and BLT switches," K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, G. Kirkman, C.G. Braun, V. Dominic, M.A.Gundersen, H. Riege and G. Mechtersheimer, IEEE Trans. Plasma Science **16** (2), 317 (1988).

3. "Fiber optic triggered high-power low-pressure glow discharge switches," C. G. Braun, W. Hartmann, V. Dominic, G. Kirkman, M. Gundersen and G. McDuff, IEEE Trans. Electron Devices **35** (4), 559 (1988).

4. "Flashlamp triggered high power thyratron type switch," G. Kirkman, W. Hartmann, and M.A. Gundersen, App. Phys. Lett. **52** (8), 613 (1988).

5. "Optoelectronic bistability in gallium phosphide," M.S. Choi, J.H. Jur, and M.A. Gundersen, App. Phys. Lett. **52** (19), 1563 (1988).

6. "Origin of anomalous emission in superdense glow discharge," W. Hartmann and M.A. Gundersen, Phys. Rev. Lett. **60** (23), 2371 (1988).

7. "Evidence for large-area superemission into a high current glow discharge," W. Hartmann, V. Dominic, G.F. Kirkman, and M.A. Gundersen, App. Phys. Lett. **53** (18), 1699 (1988).

8. "A super-emissive self-heated cathode for high-power applications," W. Hartmann, G.F. Kirkman, V. Dominic, and M.A. Gundersen, IEEE Trans. Elect. Dev. **36** (4), 825 (1989).

9. "An analysis of the anomalous high current cathode emission in pseudospark and back-of-the-cathode lighted thyratron switches," W. Hartmann, V. Dominic, G. Kirkman, and M. A. Gundersen, J. Appl. Phys. **65** (11), 4388 (1989).

10. "Phonon-assisted recombination in GaAs/AlGaAs multiple-quantum-well structures", H. H. Dai, M. S. Choi, M. A. Gundersen, H. C. Lee, P. D. Dapkus and C.W. Myles, J. App. Phys. **66** (6), 2538 (1989).

11. "A short review of plasma science for pulse power switches", M. A. Gundersen, submitted to IEEE Trans. Plasma Sci. (invited).

12. "An optically gated, glow switch Marx bank," R. Liou, H. Figueroa, Y. Hsu, G. Kirkman, and M. A. Gundersen, IEEE Trans. Elec. Dev. **37** (6), 1591 (1990).

13. "A two-component model for the electron distribution function in a high current pseudospark or back-lighted thyratron," H. Bauer, G. Kirkman, and M. A. Gundersen, IEEE Trans. Plasma Sci. **18** (2), 237 (1990).

14. "Avalanche breakdown in p-n AlGaAs/GaAs heterojunctions," J. H. Hur, C. W. Myles and M. A. Gundersen, J. Appl. Phys. **67** (11), 1 (1990).

15. "High current plasma based electron source," H. R. Bauer and M. A. Gundersen, Appl. Phys. Lett. **57** (5), 434 (1990).

16. "Penetration and equilibration of electrons in a hydrogen pseudospark-type plasma," H. R. Bauer and M. A. Gundersen, J. Appl. Phys. **68** (2), 512 (1990).

17. "GaAs based opto-thyristor for pulsed power applications," J.H. Hur, P. Hadizad, H. Zhao, S. G. Hummel, P. D Dapkus, H. R. Fetterman, and M. A. Gundersen, IEEE Trans. on Elec. Dev. **37**, 2520 (1990).

18. "Multiple-gap back-lighted thyratrons for high power applications," T. Y. Hsu, G. Kirkman, and M. A. Gundersen, IEEE Trans. on Elec. Dev. **38**, 717 (1991).

19. "Current quenching in the pseudospark," W. Hartmann, G. Kirkman, and M. A. Gundersen, Appl. Phys. Lett. **58**, 574 (1991).

20. "High current back lighted thyratron switch," G. Kirkman-Amemiya and M. A. Gundersen, submitted to Appl. Phys. Lett.

21. "A comparative study of Si and GaAs based devices for repetitive, high energy, pulsed switching applications," P. Hadizad, J. H. Hur, H. Zhao, and M. A. Gundersen, submitted to J. Appl. Phys.

22. "Lock-on effect in pulsed power semiconductor switches," M. A. Gundersen, J. H. Hur, H. Zhao, and C. W. Myles, submitted to Appl. Phys. Lett.

Book Chapters

"Studies of fundamental processes in thyratrons," D. A. Erwin, C. G. Braun, J. A. Kunc and M.A. Gundersen, "Advances in Pulsed Power Technology Volume II: Gas Discharge Closing Switches," Plenum Press (1990).

"The back-lighted thyratron," G. F. Kirkman and M. A. Gundersen, "Advances in Pulsed Power Technology Volume II: Gas Discharge Closing Switches," Plenum Press (1990).

"Plasma based concepts based on the pseudospark and BLT," M. A. Gundersen, "The Physics and Applications of Pseudosparks", NATO ASI Series B **219**, Plenum Press (1990).

"A two-electron-group model for a high current pseudospark or back-lighted thyratron plasma," H. Bauer, G. Kirkman, and M. A. Gundersen, "The Physics and Applications of Pseudosparks," NATO ASI Series B **219**, Plenum Press (1990).

"An analysis of the high current glow discharge operation of the BLT switch," G. Kirkman-Amemiya, R. L. Liou, T. Y. Hsu, and M. A. Gundersen, "The Physics and Applications of Pseudosparks," NATO ASI Series B **219**, Plenum Press (1990).

"Cathode-related processes in high-current density, low pressure glow discharges," W. Hartmann and M. A. Gundersen, "The Physics and Applications of Pseudosparks," NATO ASI Series B **219**, Plenum Press (1990).

"A review of the back-lighted thyratron physics and applications," M. A. Gundersen, "Laser Interaction and Related Plasma Phenomena," **9**, Plenum Press (1991).

"Longitudinal mode control of a CO_2 TE laser by means of intracavity absorber," R.A. Dougal, C.R. Jones, M.A. Gundersen, and L. Nelson, (previously published in Appl. Opt. **18**, 1311 (1979)), was selected for inclusion in "Selected Papers on CO_2 Lasers," Ed. James D. Evans, Milestone Series Vol. MS 22, SPIE Publications 1990.

Book:

M. A. Gundersen, Editor, with G. Schaefer, "The Physics and Applications of Pseudosparks," NATO ASI Series B **219**, Plenum Press (1990).

Other Publications:

1. "Switch developments could enhance pulsed laser performance," S. Spencer Merz and M.A. Gundersen, Laser Focus, May (1988).

2. "Preliminary results from the III-V pulsed power device research program at USC," M.A. Gundersen, Proceedings of the Semiconductor Switch Workshop, Norfolk, Virginia, May 23-24, 1988.

3. "A review of high power hollow electrode thyratron-type switches," M.A. Gundersen, Proceedings of the 1988 IEEE International Conference on Plasma Science, Seattle, Washington, June 6-8, 1988 (invited).

4. "Studies of Fundamental Processes in High Power Switches," W. Hartmann, G. Kirkman, V. Dominic and M. Gundersen, Proceedings of the European Particle Accelerator Conference, Rome, Italy, June 7-11, 1988.

5. "High power hollow cathode glow discharge switches," W. Hartmann, G. Kirkman, V. Dominic, M. A. Gundersen, and S. S. Merz, IEEE Conference Record of the Proceedings of the 1988 Eighteenth Power Modulator Symposium, 175 (1988).

6. "High current glow discharge switch with remarkable cathode properties," G. Kirkman, W. Hartmann, T.Y. Hsu, R.L. Liou, and M. A. Gundersen Proceedings of the 1988 IEEE International Electron Devices Meeting, San Francisco, California December 11-14, 1988.

7. "A plasma lens candidate with highly stable properties," G.F. Kirkman, H.Figueroa, and M.A. Gundersen, Proceedings of the 1989 Workshop on Advanced Accelerator Concepts, 217 (1989).

8. "High -power thyratron-type switch for laser applications," G. Kirkman, W. Hartmann, T.Y. Hsu, R.L. Liou, P. Ingwersen, M. Gundersen and S.S. Merz, SPIE Proceedings, 1046 (1989).

9. "New concepts for accelerator components", M.A. Gundersen, Proceedings of the Workshop on High Luminosity Asymmetric Storage Rings for B Physics, 159-172, Caltech, April 25-28 1989.

10. "Modeling of the discharge plasma in a Back Lighted Thyratron," H. Bauer, G. Kirkman, J. Kunc, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 495 (1989).

11. "Design of an opening and closing GaAs static induction transistor for pulsed power applications," P. Hadizad, J.H. Hur, M.A. Gundersen, and H.R. Fetterman, Proceedings, Seventh IEEE Pulsed Power Conference, 846 (1989).

12. "A large-area high-power superemissive cathode," W. Hartmann, R. Liou, G. Kirkman, V. Dominic, T.Y. Hsu, K. Shanahan, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 9 (1989).

13. "A GaAs-AlGaAs based thyristor", J.H. Hur, P. Hadizad, M.A. Gundersen, and H.R. Fetterman, Proceedings, Seventh IEEE Pulsed Power Conference, 341 (1989).

14. "Spectroscopic analysis of the BLT switch plasma," G. Kirkman and M. A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 491 (1989).

15. "Recent experimental studies of the BLT switch," G. Kirkman, T.Y. Hsu, R.L. Liou, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 1 (1989).

16. "Studies of multigap BLTs for high voltage applications," T.Y. Hsu, G. Kirkman, A. Litton, R. L. Liou, P. Ingwersen, H. Bauer, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 487 (1989).

17. "Avalanche breakdown in p-n AlGaAs/GaAs heterojunctions," Charles W. Myles, J.H. Hur, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 842 (1989).

18. "A high current density thyristor-like gallium phosphide based optoelectronic switch," S.D. Tsiapalas, J.H. Hur, M.S. Choi, and M.A. Gundersen, Proceedings, Seventh IEEE Pulsed Power Conference, 426 (1989).

19. "The back-lighted thyratron", in "Optics in 1989", Optics News **15**, 37 (1989), (invited).

20. "Some new applications for pseudosparks and BLT's," M. A. Gundersen, Proceedings of the 1989 Workshop on Transient Hollow Cathode Discharge Phenomena, 86 (1989).

21. "The high current glow discharge operation of the back-lighted thyratron and pseudospark switch," G. Kirkman-Amemiya, H. Bauer, R.L. Liou, T.Y. Hsu, H. Figueroa, and M.A. Gundersen, Proceedings of the 1989 Workshop on Transient Hollow Cathode Discharge Phenomena, 43 (1989).

22. "A Marx generator using back lighted switches", R. Liou, H. Figueroa, Y. Hsu, G. Kirkman-Amemiya and M.A. Gundersen, Proceedings, 1989 High Voltage Workshop, Myrtle Beach SC, October 17-19, 1989.

23. "GaAs based opto-thyristor for pulsed power applications," J. H. Hur, P. Hadizad, S. G. Hummel, K.M. Dzurko, P. D. Dapkus, M. A. Gundersen, and H. R. Fetterman, Proceedings, IEDM 1989.

24. "High current back lighted thyratron switches," G. Kirkman-Amemiya, T. Y. Hsu, R. L. Liou, and M. A. Gundersen, Proceedings of the International Magnetic Pulse Compression Workshop, Granilbakken, Lake Tahoe, 234 (1990).

25. "High-power multiple-gap back-lighted thyratrons," T. Y. Hsu, G. Kirkman, R. L. Liou, H. Figueroa, and M. A. Gundersen, Proceedings of the Nineteenth Power Modulator Symposium, 215 (1990).

26. "Avalanche breakdown characteristics of AlGaAs/GaAs p-n heterojunctions for pulsed power applications," J. H. Hur, C. W. Myles, and M. A. Gundersen, Proceedings of the Nineteenth Power Modulator Symposium, 421 (1990).

27. "High-speed static induction transistor for pulsed-power applications," P. Hadizad, J. H. Hur, H. R. Fetterman, S. Hummel, and M. A. Gundersen, Proceedings of the Nineteenth Power Modulator Symposium, 343 (1990).

28. "GaAs opto-thyristor for pulsed power applications," J. H. Hur, P. Hadizad, S. R. Hummel, P. D. Dapkus, H. R. Fetterman, and M. A. Gundersen, Nineteenth Power Modulator Symposium, 325 (1990).

29. "A study of the high-current back-lighted thyratron and pseudospark switch," G. Kirkman-Amemiya, H. Bauer, R. L. Liou, T. Y. Hsu, H. Figueroa, and M. A. Gundersen, Proceedings of the Nineteenth Power Modulator Symposium, 254 (1990).

30. "Pulsed microwave and millimeter wavelength radiation from the back-lighted thyratron," R. Liou, H.Figueroa, A. H. McCurdy, G. Kirkman-Amemiya, R. J. Temkin, H. Fetterman, and M. A. Gundersen, Proceedings of the IEEE International Electron Devices Meeting, 715 (1990).

31. "A plasma-based source of pulsed microwave and millimeter wavelength radiation," R. Liou, H. Figueroa, A. H. McCurdy, G. Kirkman-Amemiya, R. J. Temkin, H. Fetterman, and M. A. Gundersen, Proceedings of the Fifteenth International Conference on Infrared and Millimeter Waves, 149 (1990).

32. "Plasma lenses for SLAC final focus Test Facility,"D. Betz, P. Chen, D. Cline, M. A. Gundersen, C. Joshi, T. Katsouleas, J. Norem, S. Rajagopalan, J. Rosenzweig, J. J. Su, R. Williams, 1991 Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991.

33. "A novel ion beam source for electrostatic confined fusion reactors," H. Kislev, M. A. Gundersen, O. Barnouin, and G. H. Miley, ICENES 1991, Monterey, CA, June 16-21, 1991.

34. "Electron beam produced by the superemissive cathode," T. Y. Hsu, R. L. Liou, G. Kirkman-Amemiya, H. Kislev, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

35. "GaAs optoelectronic static induction transistor for high frequency pulsed power switching," P. Hadizad, J. H. Hur, J. Osinski, P. D. Dapkus, M. A. Gundersen, and H. R. Fetterman, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

36. "III-V compound based heterostructure opto-thyristor (HOT) for pulsed power applications," J. H. Hur, P. Hadizad, S. G. Hummel, P. D. Dapkus, H. R. Fetterman, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

37. "Hermetically sealed back lighted thyratron switches for high power applications," G. Kirkman-Amemiya, N. Reinhardt, M. Choi, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

38. "Solid state pulsed power device research at the University of Southern California," J. H. Hur, P. Hadizad, H. Zhao, S.G. Hummel, J.S. Osinski, P.D. Dapkus, H. R. Fetterman, C. W. Myles, and M. A. Gundersen, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

39. "High power modulator development based on the back lighted thyratron switch," G. Kirkman-Amemiya, N. Reinhardt, M.S. Choi and M. A. Gundersen, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

40. "Super-emissive cathode devices," M.A. Gundersen, G. Kirkman, R. Liou, and T. Y. Hsu, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

41. "Hollow cathode, pseudospark and back-lighted thyratron switches," M. A. Gundersen, International Conference on Phenomena in Ionized Gases, Barga, Italy, July 8-12, 1991. (Invited)

Papers presented at meetings, conferences, seminars, etc.

"Optically Triggered High Power Glow Discharge Switches," W. Hartmann, G. Kirkman, V. Dominic, and M.A. Gundersen, 1988 High-Voltage Workshop, Monterey, California, March 8-10, 1988.

"The BLT - A High Current Cold Cathode Switch," G. Kirkman, W. Hartmann, V. Dominic, and M.A. Gundersen, 1988 Tri-Service Cathode Workshop, Ft. Monmouth, New Jersey, March 22-24, 1988.

"New High Power Thyratrons," G. Kirkman and M.A. Gundersen, Argonne High Energy Physics, Advanced Accelerator Test Facility Workshop, Argonne, Illinois, April 6-7, 1988.

"Fundamental Processes in Plasma Devices," G. Kirkman and M. A. Gundersen, Argonne High Energy Physics, Advanced Accelerator Test Facility Workshop, Argonne, Illinois, April 6-7, 1988.

"Studies of Fundamental Processes in Plasma Devices," W. Hartmann, G. Kirkman, and M.A. Gundersen,Particle Beam Physics Topical Group/American Physical Society, Baltimore, Maryland, April 18-21, 1988, Bull. Am. Phys. Soc. **33**, 1082 (1988).

"New High Power Thyratrons for High Energy Physics Applications," W. Hartmann, G. Kirkman, M.A. Gundersen, K. Frank, and J. Christiansen, Particle Beam Physics Topical Group/American Physical Society, Baltimore, Maryland, April 18-21, 1988, Bull. Am. Phys. Soc. **33**, 1082 (1988).

"Optoelectronic bistability in gallium phosphide," M.S. Choi, J.H. Jur, and M.A. Gundersen, 1988 Conference on Lasers and Electro-Optics **59**, 244, Anaheim, California, April 27, 1988.

"A super-emissive cathode," M.A. Gundersen, UCLA, May 6, 1988 (invited).

"An experimental plasma lens device," M.A. Gundersen, SLAC Workshop on Plasma Lenses, Stanford, California, May 9, 1988.

"Preliminary results from the III-V pulsed power device research program at USC," M.A. Gundersen, Semiconductor Switch Workshop, Norfolk, Virginia, May 23-24, 1988 (invited).

"A review of high power hollow electrode thyratron-type switches," M.A. Gundersen, 1988 IEEE International Conference on Plasma Science, Seattle, Washington, June 6-8, 1988 (invited).

"Studies of fundamental processes in high power switches," W. Hartmann, G. Kirkman, V. Dominic, and M.A. Gundersen, European Particle Accelerator Conference, Rome, Italy, June 7-11, 1988.

"High power hollow cathode glow discharge switches," W. Hartmann, G. Kirkman, V. Dominic, and M.A. Gundersen, 18th Power Modulator Symposium, Hilton Head, South Carolina, June 20-22 1988.

"Optical diagnostic development for high current pulsed glow discharges," W. Hartmann, V. Dominic, R.L. Liou, T.Y. Hsu, and M.A. Gundersen, OPTCON '88 Technical Digest pg. 153, Santa Clara, California, Nov. 3, 1988.

"Optoelectronic bistability in gallium phosphide," M.S. Choi, J.H. Hur, and M.A. Gundersen, OPTCON '88 Technical Digest pg 183, Santa Clara, California, Nov. 4, 1988.

"A plasma lens based on a hollow cathode stable Z-pinch," G.F. Kirkman, H. Figueroa, and M.A. Gundersen, 30th Meeting of the Plasma Physics Division, American Physical Society, Hollywood, Florida, Oct. 31-Nov. 4, 1988, Bull. Am. Phys. Soc. **33** (9), 2120, Oct. (1988)

"Fundamental processes of high current (10kA/cm^2) pulsed glow discharge," G. Kirkman, Y. Hsu, R.L. Liou, and M.A. Gundersen, 30th Meeting of the Plasma Physics Division, American Physical Society, Hollywood, Florida, Oct. 31-Nov. 4, 1988, Bull. Am. Phys. Soc. **33** (9), 1947, Oct. (1988).

"Physics of a plasma switch, and applications that include a plasma lense for linear colliders", M.A. Gundersen, USC Department of Physics Atomic and Molecular Physics Seminar, Dec. 1 1988.

"High current cold cathode glow discharge switch," G. Kirkman, W. Hartmann, T.Y. Hsu, R.L. Liou, M.A. Gundersen, P. Ingwersen, and S.S. Merz, 1988 IEEE International Electron Devices Meeting, San Francisco, California, December 11-14, 1988.

"High-power thyratron-type switch for laser applications," G. Kirkman, W. Hartmann, T.Y. Hsu, R.L. Liou, M.A. Gundersen, P. Ingwersen, and S.S. Merz, SPIE's OE LASE '89, Pulse Power for Lasers II, Los Angeles, California, Jan. 19-20, 1989.

"Pulse power research issues", M.A. Gundersen, Investment Strategy Meeting on Pulse Power Technology, Wright-Patterson Air Force Base, March 14, 1989 (invited).

"The development of plasma lenses for linear colliders," J. Norem, W. Gai, R. Konecny, S. Mitingwa, J. Rosenzweig, J. Simpson, P. Schoessow, D. Cline, T. Katsouleas, C. Joshi, C. Nantista, S. Rajagopalan, P. Chen, M.A. Gundersen, H. Figureoa, and G. Kirkman, Bull. Am. Phys. Soc. **34** (2), 212, Feb. (1989); APS Particle Accelerator Conference, Chicago, IL March 20-23, 1989.

"Avalanche breakdown in p-n AlGaAs/GaAs heterojunctions," Charles W. Myles M. Gundersen, and J.H. Hur, Bull. Am. Phys. Sco. **34** (3), 1001, March (1989), American Physical Society Meeting, St. Louis, Missouri, March 20-24, 1989.

"New concepts for accelerator components", M.A. Gundersen, Workshop on High Luminosity Asymmetric Storage Rings for B Physics, California Institute of Technology, April 26, 1989.

"Transient behavior and modeling of optoelectronic bistable behavior in a gallium phosphide LED," M.S. Choi, J.H. Hur, S.D. Tsiapalas, and M.A. Gundersen, Cleo '89, CLEO/QELS '89 Advance Program, 47, Conference on Lasers and Electro-Optics, Baltimore, Maryland, April 24-28, 1989.

"New concepts for pulse power components", M.A. Gundersen, 1989 USC Industrial Associates Research Review, USC, May 12 1989.

"Modeling of the discharge plasma in a Back Lighted Thyratron," H. Bauer, G. Kirkman, and M.A. Gundersen, 16th IEEE International Conference on Plasma Science, Hyatt Regency, Buffalo, NY, May 22-24, 1989.

"Microwave reflectivities of a finite-length plasma with a periodic density variation," H. Figueroa, M.A. Gundersen, and C.Joshi, 16th IEEE International Conference on Plasma Science, Hyatt Regency, Buffalo, NY, May 22-24, 1989.

"A device for producing uniform plasmas for advanced accelerator experiments," G. Kirkman, H. Figueroa, and M.A. Gundersen, 16th IEEE International Conference on Plasma Science, Hyatt Regency, Buffalo, NY, May 22-24, 1989.

"Modeling of the discharge plasma in a Back Lighted Thyratron," H. Bauer, G. Kirkman, J. Kunc, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"Design of an opening and closing GaAs static induction transistor for pulsed power applications," P. Hadizad, J.H. Hur, M.A. Gundersen, and H.R. Fetterman, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"A large-area high-power superemissive cathode," W. Hartmann, R. Liou, G. Kirkman, V. Dominic, T.Y. Hsu, K. Shanahan, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"A GaAs-AlGaAs based thyristor," J.H. Hur, P. Hadizad, M.A. Gundersen, and H.R. Fetterman, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"Spectroscopic analysis of the BLT switch plasma," G. Kirkman and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"Recent experimental studies of the BLT switch," G. Kirkman, T.Y. Hsu, R. L. Liou, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"Studies of multigap BLTs for high voltage applications," T.Y. Hsu, G. Kirkman, A. Litton, R. L. Liou, P. Ingwersen, H. Bauer, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"Avalanche breakdown in p-n AlGaAs/GaAs heterojunctions," Charles W. Myles, J.H. Hur, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"A high current density thyristor-like gallium phosphide based optoelectronic switch," S.D. Tsiapalas, J.H. Hur, M.S. Choi, and M.A. Gundersen, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989.

"An analysis of the high current flow discharge operation of the BLT switch", G.F. Kirkman-Amemiya and M.A. Gundersen, NATO Advanced Research Workshop on the Physics and Applications of High Power Hollow Electrode Glow Switches, Lillehammer, Norway, July 17-21, 1989.

"New research directions," M.A. Gundersen, NATO Advanced Research Workshop on the Physics and Applications of High Power Hollow Electrode Glow Switches, Lillehammer, Norway, July 17-21, 1989.

"A two-electron-group model for a high current pseudospark or back-lighted thyratron plasma," H. Bauer, G. Kirkman, and M. A. Gundersen, NATO Advanced Research Workshop on the Physics and Applications of High Power Hollow Electrode Glow Switches, Lillehammer, Norway, July 17-21, 1989.

"Cathode-related processes in high-current density, low pressure glow discharges," W. Hartmann and M. A. Gundersen, NATO Advanced Research Workshop on the Physics and Applications of High Power Hollow Electrode Glow Switches, Lillehammer, Norway, July 17-21, 1989.

"A partial summary of pulse power research activities at the University of Southern California," M.A. Gundersen, The Second SDIO/ONR Pulse Power Physics Meeting, San Diego, California, July 25-26, 1989.

"Some new applications for pseudosparks and BLT's," M. A. Gundersen, Transient Hollow Cathode Discharge Phenomena Workshop, Paris, Sept. 11-12, 1989.

"The high current glow discharge operation of the back-lighted thyratron and pseudospark switch," G. Kirkman-Amemiya, H. Bauer, R.L. Liou, T.Y. Hsu, H. Figueroa, and M.A. Gundersen, Transient Hollow Cathode Discharge Phenomena Workshop, Paris, Sept. 11-12, 1989.

"A Marx generator using back lighted switches", R. Liou, H. Figueroa, Y. Hsu, G. Kirkman-Amemiya and M.A. Gundersen, 1989 High Voltage Workshop, Myrtle Beach SC, October 17-19, 1989.

A review of the back lighted thyratron and its applications", Sixth Key Technologies Scorr Group Meeting, Huntington Beach CA, 23-27 October 23-27, 1989. (invited).

"The back-lighted thyratron", Lawrence Livermore National Laboratory, November 8, 1989 (invited).

"A review of the back-lighted thyratron physics and applications," M. A. Gundersen, 9th Intl. Workshop on Laser Interaction and Related Plasma Phenomena, Monterey, CA, Nov. 6-10, 1989 (invited).

"A proposed microwave plasma mirror," H. Figueroa and M. A. Gundersen, 9th Intl. Workshop on Laser Interaction and Related Plasma Phenomena, Monterey, CA, Nov. 6-10, 1989.

"Analysis of the high current glow discharge occurring in the BLT and pseudospark switch", G. Kirkman-Amemiya, H. Bauer and M.A. Gundersen, Thirty-first APS Plasma Physics Meeting, November 13-17, 1989.

"GaAs based opto-thyristor for pulsed power applications," J. H. Hur, P. Hadizad, S. G. Hummel, K.M. Dzurko, P. D. Dapkus, M. A. Gundersen, and H. R. Fetterman, 1989 IEEE Electron Devices Meeting, Washington D.C., December 1989.

"Plasma devices based on the back lighted thyratron," M. A. Gundersen, Lawrence Berkeley Laboratory, January 12, 1990 (invited).

"High current back lighted thyratron switches," G. Kirkman-Amemiya, T. Y. Hsu, R. L. Liou, and M. A. Gundersen, International Magnetic Pulse Compression Workshop, Granilbakken, Lake Tahoe, Feb. 12-14, 1990.

"Temperature and composition dependence of avalanche breakdown in $Al_xGa_{1-x}As/GaAs$ heterojunctions," C. W. Myles, J. H. Hur, and M.A. Gundersen, American Physical Society, 1990 March Meeting, Anaheim, CA March 12-16, 1990, Bull. Am. Phys. Soc. **35** (3), 738 (1990).

"Multigap BLT's for high power applications," T-Y. Hsu, G. Kirkman-Amemiya, R-L. Liou, H. Figueroa, and M.A. Gundersen, Spring Meeting of the American Physical Society, Division of Physics of Beams, Washington, D.C., April 16-19, 1990, Bull. Am. Phys. Soc. **35** (4), 1002 (1990).

"Pulsed electron beam production in the back-lighted thyratron," G. Kirkman-Amemiya, H. Bauer, R. Liou, H. Figueroa, T-Y. Hsu, A. H. McCurdy, and M.A. Gundersen, Spring Meeting of the American Physical Society, Division of Physics of Beams, Washington, D.C., April 16-19, 1990, Bull. Am. Phys. Soc. **35** (4), 1002 (1990).

"A high power thyratron type switch for high energy physics," M. A. Gundersen, G. Kirkman-Amemiya, R. L. Liou, and T-Y. Hsu, Spring Meeting of the American Physical Society, Division of Physics of Beams, Washington, D.C., April 16-19, 1990, Bull. Am. Phys. Soc. **35** (4), 1002 (1990).

"A study of the high current discharge of the pseudospark and back lighted thyratron switch," G. Kirkman-Amemiya, H. Bauer, R. L. Liou, T. Y. Hsu, H. Figueroa, and M. A. Gundersen, 1990 IEEE International Conference on Plasma Science, May 21-23, 1990.

"A plasma-based source of pulsed microwave and millimeter wavelength radiation," R. L. Liou, H. Figueroa, G. Kirkman-Amemiya, R. J. Temkin, A. H. McCurdy, H. Fetterman, and M. A. Gundersen, 1990 IEEE International Conference on Plasma Science, May 21-23, 1990.

"High-power multiple-gap back-lighted thyratrons," T. Y. Hsu, G. Kirkman, R. L. Liou, H. Figueroa, and M. A. Gundersen, Nineteenth Power Modulator Symposium, San Diego, California, June 26-28, 1990.

"Avalanche breakdown characteristics of AlGaAs/GaAs p-n heterojunctions for pulsed power applications," J. H. Hur, C. W. Myles, and M. A. Gundersen, Nineteenth Power Modulator Symposium, San Diego, California, June 26-28, 1990.

"High-speed static induction transistor for pulsed-power applications," P. Hadizad, J. H. Hur, H. R. Fetterman, S. Hummel, and M. A. Gundersen, Nineteenth Power Modulator Symposium, San Diego, California, June 26-28, 1990.

"GaAs opto-thyristor for pulsed power applications," J. H. Hur, P. Hadizad, S. R. Hummel, P. D. Dapkus, H. R. Fetterman, and M. A. Gundersen, Nineteenth Power Modulator Symposium, San Diego, California, June 26-28, 1990.

"A study of the high-current pseudospark and back-lighted thyratron switch," G. Kirkman-Amemiya, H. Bauer, R. L. Liou, T. Y. Hsu, H. Figueroa, and M. A. Gundersen, Nineteenth Power Modulator Symposium, San Diego, California, June 26-28, 1990.

"A review of some recent USC pulsed power physics research," M. A. Gundersen, Third SDIO/ONR Pulse Power Physics Meeting, Norfolk, VA, August 2-3, 1990.

"Super-emissive cathode switches", M.A. Gundersen, High Average Power Switching Workshop, Lawrence Livermore National Laboratory, Livermore, CA, October 10-11 1990.

"GaAs opto-thyristor for pulsed power applications," J. H. Hur, P. Hadizad, S. G. Hummel, P. D. Dapkus, H. R. Fetterman, and M. A. Gundersen, OPTCON '90, Boston, MA, November 4-9, 1990.

"Super-emissive cathodes and their applications," M. A. Gundersen, Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, MA, November 6, 1990.

"Pulsed microwave and millimeter wavelength radiation from the back-lighted thyratron," R. Liou, H.Figueroa, A. H. McCurdy, G. Kirkman-Amemiya, R. J. Temkin, H. Fetterman, and M. A. Gundersen, 1990 IEEE International Electron Devices Meeting, San Francisco, California, December 12, 1990.

"A plasma-based source of pulsed microwave and millimeter wavelength radiation," R. Liou, H. Figueroa, A. H. McCurdy, G. Kirkman-Amemiya, R. J. Temkin, H. Fetterman, and M. A. Gundersen, 15th International Conference on Infrared and Millimeter Waves, Orlando, Florida, December 10-14, 1990.

"Model for the "lock-on effect" in semiconductor switches," H. Zhao, J. Hur, P. Hadizad, M. Gundersen, and C. W. Myles, Bull. Am. Phys. Soc. **36** (3), 985, March (1989); APS Particle Accelerator Conference, Cincinnati, OH, March 18-22, 1991.

"High-voltage, > 100kV hermetically sealed back lighted thyratron switches," G. Kirkman-Amemiya, N. Reinhardt, M. Choi, and M. A. Gundersen, 1991 High-Voltage Workshop, Naval Ship Weapons Systems Engineering Station, Port Heuneme, CA, March 19-21, 1991.

"Electron beam generation in the superemissive cathode," T. Y. Hsu, R. L. Liou, G. Kirkman-Amemiya, and M. A. Gundersen, 1991 Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991; Bull. Am. Phys. Soc. **36** (4), 1591 (1991).

"Fast risetime BLT switches for accelerator applications," G. Kirkman-Amemiya, N. Reinhardt, M. Choi and M. A. Gundersen, 1991 Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991; Bull. Am. Phys. Soc. **36** (4), 1515 (1991).

"Plasma lenses for SLAC final focus Test Facility,"D. Betz, P. Chen, D. Cline, M. Gundersen, C. Joshi, T. Katsouleas, J. Norem, S. Rajagopalan, J. Rosenzweig, J. J. Su, R. Williams, 1991 Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991.

"Optically gated GaAs thyristors for pulsed power switching," J. H. Hur, P. Hadizad, H. Zhao, S. G. Hummel, P.D. Dapkus, H. R. Fetterman, C. W. Myles, and M. A. Gundersen, CLEO '91 Conference on Lasers and Electro-Optics, Baltimore, MD, May 12-17, 1991.

"The superemissive cathode as an electron beam source," T.Y. Hsu, R. L. Liou, G. Kirkman-Amemiya, and M. A. Gundersen, 18th IEEE International Conference on Plasma Science, June 3-5, 1991.

"A novel ion beam source for electrostatic confined fusion reactors," H. Kislev, M. A. Gundersen, O. Barnouin, and G. H. Miley, ICENES 1991, Monterey, CA, June 16-21, 1991.

"Electron beam produced by the superemissive cathode," T. Y. Hsu, R. L. Liou, G. Kirkman-Amemiya, H. Kislev, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

"GaAs optoelectronic static induction transistor for high frequency pulsed power switching," P. Hadizad, J. H. Hur, J. Osinski, P. D. Dapkus, M. A. Gundersen, and H. R. Fetterman, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

"III-V compound based heterostructure opto-thyristor (HOT) for pulsed power applications," J. H. Hur, P. Hadizad, S. G. Hummel, P. D. Dapkus, H. R. Fetterman, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

"Hermetically sealed back lighted thyratron switches for high power applications," G. Kirkman-Amemiya, N. Reinhardt, M. Choi, and M. A. Gundersen, 8th IEEE Pulsed Power Conference, San Diego, CA, June 17-19, 1991.

"Solid state pulsed power device research at the University of Southern California," J. H. Hur, P. Hadizad, H. Zhao, S.G. Hummel, J.S. Osinski, P.D. Dapkus H. R. Fetterman, C. W. Myles, and M. A. Gundersen, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

"High power modulator development based on the back lighted thyratron switch G. Kirkman-Amemiya, N. Reinhardt, M.S. Choi and M.A. Gundersen, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

"Super-emissive cathode devices," M.A. Gundersen, G. Kirkman, R. Liou, and Y. Hsu, 4th SDIO/ONR Pulsed Power Meeting, Los Angeles, CA, June 20-21, 1991.

"Hollow cathode and super-emissive cathode properteis of pseudosparks and back-lighted thyratrons," M.A. Gundersen, International Conference on Phenomena in Ionized Gases, Barga, Italy, July 8-12, 1991. (Invited)

Patents:

Light initiated high power electronic switch (U.S. Patent 4,771,168, Sept. 13, 1988).

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Lock-on effect in pulsed power semiconductor switches

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ABSTRACT

Certain high voltage pulsed power switches based on semi-insulating GaAs or InP exhibit a "lock-on" effect. In this paper, this effect is argued to be fundamentally a transferred-electron effect, and its experimentally observed characteristics are explained. The lock-on effect causes high forward drop and high power dissipation for certain pulsed power switches based on GaAs and various other direct gap materials.

Pulsed power devices based on semi-insulating (SI) GaAs or InP are observed to exhibit a unique property, commonly called the "lock-on" effect. This effect is most conspicuous in bulk switches comprised of undoped or Cr-doped GaAs and Fe-doped InP,[1-5] but is also observed in junction devices with thick SI GaAs base layers.[6] Figure 1 shows the results of a typical experiment in which an opto-thyristor with a 200-μm SI GaAs:Cr base layer is optically triggered. In the ON-state, the device locks on or latches on to a forward drop voltage of ~100 V or field of ~5 kV/cm. In this paper, a model that can explain all the experimentally observed characteristics of the lock-on effect is presented, but more importantly, implications of this model for materials under consideration for pulsed power applications are discussed.

Any model of the lock-on effect must qualitatively and quantitatively explain the experimentally observed characteristics of this effect, which include the following:[1-6]

- It is observed in devices fabricated with SI GaAs or InP but usually not with Si,[3,4] and is usually triggered into the lock-on state with an optical or electron beam.[1-6]
- The current vs. voltage (I-V) characteristic of a lock-on device is of the current-controlled negative differential resistivity (CCNDR) type or the S-type (schematically shown in the bottom inset of Fig. 1), and has two distinct features: a low-current, OFF-state branch, characterized by a threshold voltage (V_{th}); and a current-independent, ON-state branch, characterized by a lock-on voltage (V_{lo}).
- The lock-on electric field for a given material is independent of the lock-on state current and the pre-trigger bias field, and is substantially larger for InP than for GaAs. Typical fields are ~5 kV/cm for GaAs:Cr in opto-thyristors,[6] ~8.5 kV/cm for GaAs:Cr photoconductive switches,[4] ~3.6 kV/cm for undoped GaAs,[4] ~4.8 kV/cm for GaAs:Cu:Si,[2] and 14.4 kV/cm for InP:Fe.[3]

- With higher defect density, the lock-on voltage is larger. A neutron bombarded GaAs sample showed a lock-on field of ~49 kV/cm with minimum pre-trigger bias of 67.5 kV/cm.[3]
- At lower temperature, the lock-on field is smaller. For a GaAs:Cr sample, the lock-on field decreased from ~8 kV/cm at room temperature to ~6.2 kV/cm at 77 K.[3]
- The pre-trigger bias field must be larger than a certain minimum field that is greater than the lock-on field. For InP:Fe, ~28.2 kV/cm were required before locking on to 14.4 kV/cm;[3] for GaAs:Cu:Si, ~10 kV/cm were needed before locking on to 4.8 kV/cm.[2]

Double injection has been proposed as a possible mechanism for lock-on,[7] and internal reabsorption of recombination radiation was used to explain the CCNDR observed in SI GaAs:Cr p-i-n diodes.[8] These models may be able to reproduce qualitatively the lock-on behavior, but cannot account for all the lock-on characteristics quantitatively. We argue here that the lock-on effect is fundamentally related to the transferred-electron (TE) effect[9] and instabilities associated with it. This explanation is supported by the observation of the lock-on effect in GaAs and InP (which have bandstructures that favor the TE effect) but not in Si (which has a bandstructure that does not).

The presence of a larger concentration of native defects in GaAs and InP than is found in Si can also strongly affect the I-V characteristics of these materials. Such defect related effects are accounted for in our model, which includes the trapping-scattering effects of deep levels. However, we show elsewhere[10] that the same type of material bandstructure which is responsible for the TE effect[9] is also necessary for lock-on to occur. In particular, in our model, a conduction bandstructure like those of GaAs and InP with a lower-lying, small effective mass (high mobility) direct-gap valley and a higher-lying, large effective mass (low mobility) indirect-gap valley is required.

We also note, in passing, that I-V characteristics of the CCNDR type have also been observed in Si p-i-n structures.[11] However, the mechanisms responsible for the behavior are very different than the bandstructure related mechanism responsible for the TE effect. Thus, within our model, they are unrelated to the lock-on effect also.

An explanation of lock-on based on the TE effect has previously been proposed by others,[4,12,13] but their analyses were either incomplete or inconclusive. In addition to the TE effect, the present model includes impact ionization due to high field charge domains, trapping-scattering effects due to deep levels, and filament formation. While all of these effects are found to be essential in determining the details of the lock-on characteristics, such as, for example, the threshold field for lock-on, the lock-on effect itself is fundamentally related to the same conduction bandstructure characteristics responsible for the TE effect. We distinguish between threshold effect, wherein collisional processes resulting from the presence of scattering centers can result in lock-on and the physical mechanism responsible for lock-on which is a bandstructure effect.

The TE effect leads to a negative-differential mobility (NDM) which is unstable against the formation of one or more high-field domains when the biased field is above the NDM threshold field.[9] In lock-on devices, because of the high resistance of the SI material, a large field can be maintained across the device before triggering. Once the device is triggered, the trigger-beam generated carriers cause high-field domains to form. In our model, the high field in the domain generates more carriers through impact ionization, and the device makes a transition to the lock-on state. The impact ionization within the high-field domain competes with the trapping effect of the deep levels, and interaction of these two processes determines the characteristics of the lock-on effect.

The filament conduction is necessary in lock-on devices to explain the voltage-limiter-like characteristic in the ON-state branch of the I-V curve. It is commonly accepted that CCNDR in the J-V curve of a device is unstable against the formation of filaments,[14] and this leads to a voltage-limiter-like behavior in the I-V curve (bottom inset of Fig. 1). The limiting voltage is determined by the minimum voltage in the NDR region of J-V curve, and the filament radius is determined by the device current. In our model, this limiting voltage is same as the lock-on voltage, and its experimentally observed characteristics are explained.

The higher lock-on field for InP (compared to that for GaAs) is, at least semi-quantitatively, explained in our model by the bandstructure difference in the two materials. In particular, the L-valley minimum of InP is ~0.53 eV above the Γ-valley minimum and is larger than the difference between the two minima in GaAs, which is ~0.31 eV. Consequently, the ratio of the NDM threshold field for InP to that for GaAs is ~3.3.[9] For the one case where it has been measured, the observed lock-on field for SI InP is larger than that for SI GaAs by a factor which depends on the measurement conditions and the type and density of defects in the GaAs material.[3] In most cases, however, the factor is very similar to above ratio.

The effect of defect density on the lock-on voltage is explained within our model by noting its effects on carrier scattering and trapping. For SI materials, the density of neutral deep impurity centers is much larger than the density of trapped centers which are usually negatively charged. For neutral impurity scattering, the relaxation time is inversely proportional to the impurity density.[15] With high defect density, therefore, the scattering relaxation time is short, and a large electric field is needed for carriers to attain enough energy to transfer to the satellite valley after collisions. In addition, the carrier trapping rate is directly proportional to the deep level density. Therefore, for materials with a high density of deep levels, a high field is needed to increase the impact ionization rate and balance the high trapping rate.[10]

Deep impurity scattering modifies the velocity-field relationship, and thus the mobility of the material. It is reasonable to assume that the low-field mobility would decrease and the NDM threshold field would increase with the increasing density of deep impurities. Incorporating this effect into our model, the NDM threshold field can be obtained once the low-field mobility is known. For undoped GaAs the low-field mobility is ~6000 cm^2/V-s,[16] and for GaAs:Cr, the low-field mobility is ~4400 cm^2/V-s.[17] In our model, these mobilities respectively give predicted NDM threshold fields of 3.7 kV/cm and 5.1 kV/cm.[10] These numbers are very similar to the observed lock-on fields for these two types of GaAs material. Ideally, measured low field mobilities for the same samples as used in the lock-on measurements should be used in the calculations, and this might alter slightly the above predicted fields. Since this is not possible, we have used mobilities from the literature[16,17] in these initial calculations. Nevertheless, the similarity in the computed results and the observed lock-on fields should indicate that our model is at lest semi-quantitatively correct.

The effect of the temperature on the lock-on field is related, in our model, to the temperature dependence of scattering mean free path. The mean free path increases as the temperature decreases. Thus, a low field is needed to scatter electrons to the satellite valley. It has been shown experimentally that for n-type GaAs the negative-differential-mobility (NDM) threshold field linearly decreases with temperature.[18] The ratio of NDM threshold field at 300 K to that at 77 K is very similar to the ratio of corresponding lock-on fields at these temperatures.[10]

The requirement of a certain minimum bias field for triggering lock-on is related to the requirement of minimum concentration of carriers that must be generated initially before a domain can form and the device can make a transition to the lock-on state. This requirement affects the threshold behavior and not the lock-on field itself. With a low-power triggering beam, a large pre-trigger bias field is necessary to switch the device into lock-on since the impact-ionization generation rate, which is a function of carrier concentration and field, must be larger than the trapping rate.[10] Otherwise, the device would operate in a photoconductive mode.

Some important conclusions pertaining to pulsed power switching can be made on the basis of our model. The most important of these is that since the TE effect is expected in most direct gap semiconductors that have indirect gap minima with large effective masses, the lock-on effect should also occur in such materials. Semiconductors that have displayed the TE effect include GaAs, InP, CdTe, InAs, InSb, ZnSe, and many ternary and quaternary compounds. The lock-on effect must therefore be considered when using these materials in pulse power switching devices. Pulsed power switches—as distinct from other switches including fast, high voltage switches that transfer small energies—are required to hold off large voltages (≥ 1 kV), switch large currents (≥ 1 kA), and transfer large pulse energies to a load (> several joules). In a typical application, a switch might be used to hold off 25 kV, switch a peak current of 5-10 kA, and transfer ~20 J of energy. It is often of importance that switches designed for such applications transfer energy efficiently—particularly when high repetition rates are required. The lock-on effect thus poses an intrinsic limitation for bulk (such as photoconductive) or bulk-type (such as a thyristor with a thick base required for high hold-off voltage) pulsed power switches based on materials where the TE effect can occur. For example, GaAs devices that are ≥ 100 μm thick may be expected to have a forward drop of ≥ 50 V, which will be excessive for many high current applications. Similar limitations may be expected for the other materials listed above. Thus, materials in which the TE effect can occur may not be suitable candidates for switching applications where low output impedance is required of the modulators.

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FIGURE CAPTIONS

Fig. 1. Typical profiles of current (the upper curve) and voltage (the lower curve) in a pulse-forming line switched with a GaAs opto-thyristor.[6] In the ON state, the voltage across the device is ~100 volts, corresponding to a field of ~5 kV/cm. Top inset: A cross section of the GaAs opto-thyristor structure with Cr-doped, Bridgman grown, semi-insulating GaAs base layer. Bottom inset: Schematic representation of current-density vs. voltage (J-V) and current vs. voltage (I-V) curves of lock-on devices. The lock-on devices exhibit a current-controlled negative resistivity (CCNDR).

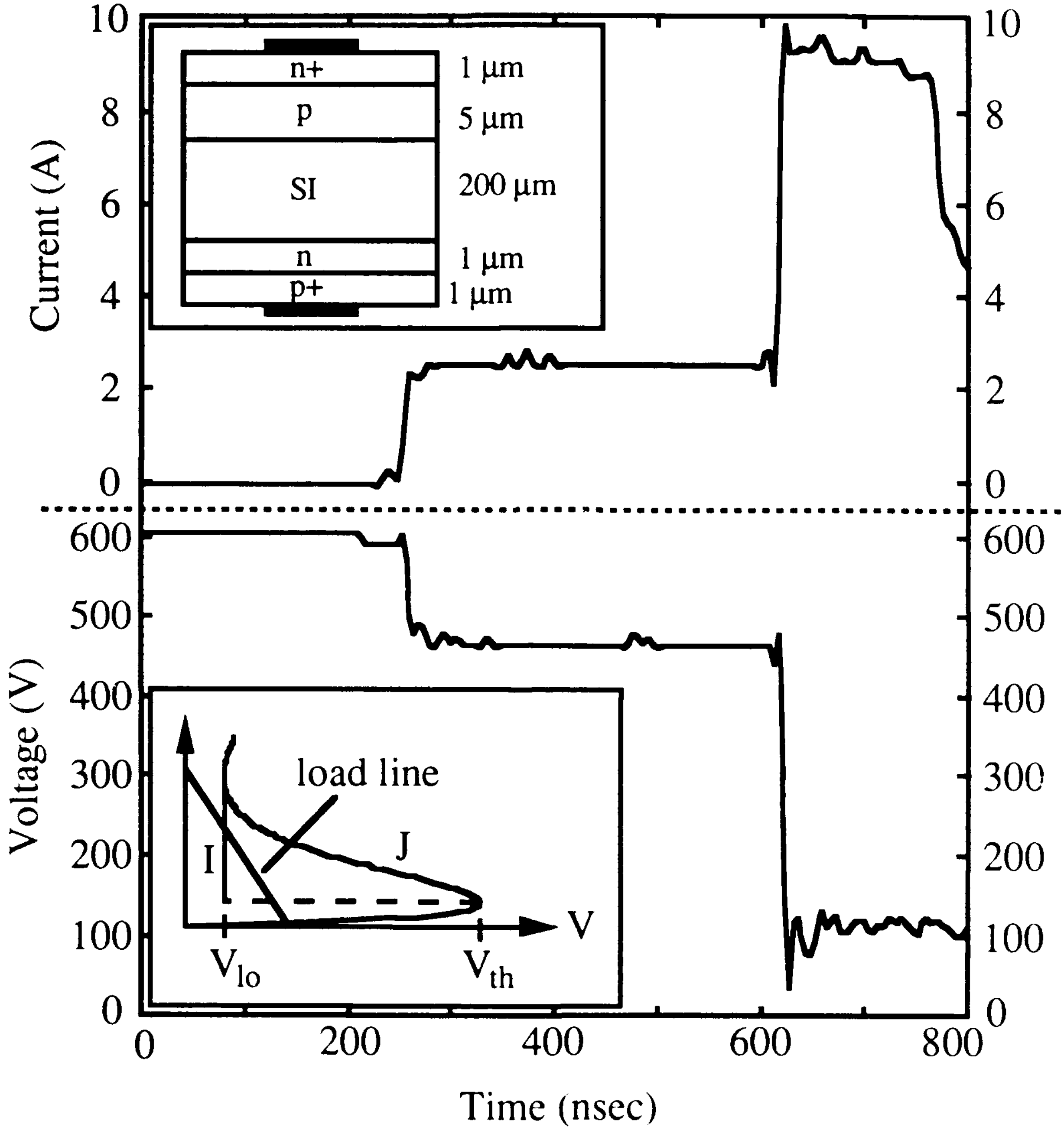

FIGURE 1. GUNDERSEN ET AL

REFERENCES

[1]K.H. Schoenbach, V.K. Lakdawala, D.C. Stoudt, T.F. Smith and R.P. Brinkmann, IEEE Trans. Electron Devices **ED-36**, 1793 (1989).

[2]M.S. Mazzola, K.H. Schoenbach, V.K. Lakdawala, R. Germer, G.M. Loubriel and F.J. Zutavern, Appl. Phys. Lett. **54**, 742 (1989).

[3]G.M. Loubriel, F.J. Zutavern, H.P. Hjalmarson and M.W. O'Malley, in *Digest of Technical Papers, 7th IEEE Pulsed Power Conference*, Monterey, California, June 1989, edited by R. White and B.H. Bernstein (IEEE, New York, 1989), pp. 365-367.

[4]F.J. Zutavern, G.M. Loubriel, B.B. McKenzie, W.M. O'Malley, R.A. Hamil, L.P. Schanwald and H.P. Hjalmarson, in *Digest of Technical Papers, 7th IEEE Pulsed Power Conference*, Monterey, California, June 1989, edited by R. White and B.H. Bernstein (IEEE, New York, 1989), pp. 412-417.

[5]R.L. Druce, M.D. Pocha, K.L. Griffin and W.W. Hofer, in *Digest of Technical Papers, 7th IEEE Pulsed Power Conference*, Monterey, California, June 1989, edited by R. White and B.H. Bernstein (IEEE, New York, 1989), pp. 882-886.

[6]J.H. Hur, P. Hadizad, S.R. Hummel, P.D. Dapkus, H.R. Fetterman and M.A. Gundersen, IEEE Trans. Electron Devices **37**, 2520 (1990).

[7]R.P. Brinkmann, K.H. Schoenbach and D.C. Stoudt, Old Dominion University, Physical Electronics Research Institute, Publication Series No. 105, June 1990.

[8]P.R. Selway and W.M. Nicolle, J. Appl. Phys. **40**, 4087 (1969).

[9]S.M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981).

[10]H. Zhao, J.H. Hur, P. Hadizad, C.W. Myles and M.A. Gundersen (unpublished).

[11]For example, N. Holonyak, Jr., Proc. IRE **50**, 2421 (1962).

[12]W.T. White, III, C.G. Dease and G.H. Khanaka, in *Digest of Technical Papers, 7th IEEE Pulsed Power Conference*, Monterey, California, June 1989, edited by R. White and B.H. Bernstein (IEEE, New York, 1989), pp. 422-425.

[13]E.E. Kunhardt (private communication).

[14]D. Adler. M.S. Shur, M. Silver and S.R. Ovshinsky, J. Appl. Phys. **51**, 3289 (1980).

[15]C. Erginsoy, Phys. Rev. **79**, 1013 (1950).

[16]M.L. Gray, L. Sargent, K.M. Burke, K.A. Grim and J.S. Blakemore, J. Appl. Phys. **63**, 4413 (1988).

[17]D.C. Look, in *Semiconductors and Semimetals*, edited by R.K. Willardson and A.C. Beer, vol. 19 (Academic Press, New York, 1983), pp. 75-170.

[18]I. Mojzes, B. Podor and I. Ealogh, Phys. Status Solidi A, 39, K123 (1977).